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SIMULATION OF THE EFFECTS OF INCREASED TRUCK  
SIZE AND WEIGHT

Final Summary Report

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16. Abstract <p>A computer program for simulating the braking and directional response of heavy vehicles has been developed for the Federal Highway Administration as a tool for investigation of the effects of increased truck size and weight. Designated as the "Truck and Tractor-Trailer Dynamic Response Simulation - T3DRS:V1," the program is capable of simulating trucks, tractor-semitrailers, doubles and triples combinations. Modeling for the vehicle components has been adapted from earlier simulations produced under sponsorship of the Motor Vehicle Manufacturers Association. The T3DRS:V1 version consolidated all vehicle combinations into one program with improved input/output format, a new closed-loop path-following steering option, optional side-to-side differences on all paired components, a simplified tandem axle suspension model, and more versatility in the choice of output information. The program has been validated against analytical models, predecessor simulation programs and vehicle test data acquired separately by the Texas Transportation Institute and the Highway Safety Research Institute. The simulation program has achieved operational status on FHWA computer facilities and a training seminar was held to introduce users to the program.</p> <p>Volume II is a technical report with appendices.</p>			
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## 1.0 INTRODUCTION

This document reports on the research project entitled "Simulation of the Effects of Increased Truck Size and Weight," conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan. The research was sponsored by the Federal Highway Administration (FHWA) under Contract Number DOT-HS-11-9330, extending over the period from October 1977-November 1979.

The Federal-Aid Highway Act of 1956 authorized the construction of the National System of Interstate and Defense Highways and placed certain limitations on the dimensions and weights of vehicles operating on the system. The limitations imposed were: 18,000 pounds (8165 Kg) on a single axle, 32,000 pounds (14,515 Kg) on a tandem axle, an overall gross weight of 73,280 pounds (33,240 Kg), and a width of 96 inches (244 cm). These limits were based on considerations of system capacity, strength of existing pavement and bridges, the need for maintenance and resurfacing, the highway geometrics required to accommodate larger vehicles, and the effects of large trucks on traffic operations.

The weight limitations have since been raised to 20,000 pounds (9,072 Kg) for a single axle, 34,000 pounds (15,422 Kg) for a tandem axle and 80,000 pounds (36,288 Kg) total gross weight for the vehicle combination. Increasing loads have broad implications on the operation of the highway system. For example, the 11% increase in single-axle load has significance because it is the basis for the structural design of pavements and is also a primary factor in vehicle control.

Proposals are being made to further increase the allowable loads, as well as raise the width limitations, and it must be anticipated that more such proposals will be submitted from time to time. Such proposals should be evaluated on a rational basis, and should consider the economic and social impacts as well.

With the emergence of high-speed computers, the simulation of complex processes has become a reliable and cost-effective method for investigating the performance of new concepts or the effects of modifications to existing systems. Computer codes enabling the simulation of the ride and handling

of heavy trucks have been developed and are operational. It follows that such programs, together with some experimental and field data, offer considerable promise for aiding the Federal Highway Administration in conducting analyses that are needed for rational decision making.

To this end, HSRI has been supported by the FHWA in a program designed to modify and exercise computer simulation programs for investigating the dynamics of heavy vehicle trains, their response to control inputs, and their stability in the presence of disturbance inputs. The approach adopted in the study was that of selecting an existing simulation program for trucks and tractor-trailers and modifying it as necessary to meet the above stated objectives. To establish the veracity of this work, a separate project entitled "Validation of Truck Handling Simulation Results" was sponsored concurrently at the Texas Transportation Institute/Texas A & M University, to generate full-scale vehicle test data against which the computer simulation program could be validated. The research plan called for using the validated program in a prototype study of truck size and weight effects, and a copy of the program was to be vested with the Federal Highway Administration for use at their own computer facilities.

This report summarizes the development and the features of the computer code prepared to satisfy the needs and requirements of the FHWA. This summary includes:

- 1) a statement of the background underlying the development of the program,
- 2) a description of the program,
- 3) a definition of the uses of the program, and
- 4) a brief report of validation activities.

The report concludes with a presentation of findings and recommendations with respect to follow-on use of the program by the FHWA.

## 2.0 DEVELOPMENT OF THE T3DRS:V1 PROGRAM

### 2.1 Background

Since 1971, the HSRI has conducted research under the sponsorship of the Motor Vehicle Manufacturers Association (MVMA) to develop computer-based methods for analyzing and predicting the directional and braking response of commercial motor vehicles. The initial phase of this research dealt with modeling the braking performance of commercial vehicles and was reported in Reference [1]\* (Phase I). The second phase extended vehicle modeling to allow for directional response and was reported in Reference [2] (Phase II). The continuation of research into braking performance led to additional refinements in the braking simulation which were reported in Reference [3] (Phase III). In total, this research under the auspices of MVMA led to four separate computer simulation models:

- Straight Truck Braking Model (Phase I & III)
- Tractor-Trailer Braking Model (Phase I & III)
- Straight Truck Directional Response Model (Phase II)
- Tractor-Trailer Directional Response Model (Phase II)

Though all programs evolved from the same approach to vehicle modeling, separate programs were prepared and maintained.

Under this project, the requirements to add one or two full trailers (doubles and triples) to the tractor-semitrailer model were cause for reformulating the computer simulation model for the purposes of:

Consolidating all vehicle combinations into one program

Improving the input/output format

Simplifying the model to include only the most relevant aspects as determined from the intervening research.

The work led to a new simulation program using the same modeling approaches. The program, described here, is designated as "The Truck and Tractor-Trailer Dynamic Response Simulation - T3DRS:V1."

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\*Numbers in brackets indicate references in Section 5 of this report.

## 2.2 Description of the Program

The T3DRS:V1 program is a time domain mathematical simulation of a truck/tractor, a semitrailer and up to two full trailers. The vehicles are represented by differential equations derived from Newtonian mechanics that are solved at successive time increments by digital integration. A more detailed description of the program is provided in the User's Manual [4] and Programmer's Manual [5] prepared under this project.

The program is written in a generalized fashion to allow simulation of a large number of vehicle configurations. The first vehicle is the power unit and may be a truck or tractor, both of which may carry payload. As a single unit with no payload, it is equivalent to an empty truck or bobtail tractor. With payload, it is a truck, which, with a semitrailer as well, simulates a car hauler, dromedary tractor, etc. The second unit is always a semitrailer (i.e., current models do not include a truck with full trailer). The third and fourth units are full trailers consisting of semitrailers on either a fixed or converter dolly. Separate payload may be specified for each trailer.

The truck/tractor unit is distinguished by the fact that it can have only a single front axle with single tires, and can be arbitrarily steered. All other axles on the vehicle combination can be represented as single or tandem axles with single or dual wheel sets.

The mathematical model effectively incorporates up to 71 degrees of freedom. The number of degrees of freedom are dependent on the vehicle configuration and derive from the following:

- Six degrees of freedom (three translational and three rotational) for the truck/tractor sprung mass
- Three degrees of freedom for the semitrailer (the three other degrees of freedom of the semitrailer are effectively eliminated by dynamic constraints at the hitch)
- Five degrees of freedom for each of the two full trailers allowed
- Two degrees of freedom (vertical and roll) for each of the 13 axles allowed



- A wheel rotation degree of freedom for each of the 26 wheels allowed

The motion of each of the sprung masses is determined from the summation of forces and moments upon it arising from the tires (acting through the unsprung mass of the axle and suspension), gravity and the hitch point constraints. Small angle assumptions are made in the derivation of the mathematical equations so that the simulation can be validly applied up through the onset of rollover.

Operation of the T3DRS:V1 program is accomplished by submission of the necessary job control instructions followed by a list of input parameters. The specific job control instructions required are dependent on the user's computer system and whether batch or remote job entry is being used.

The list of parameters describes the vehicle being simulated and the maneuver being performed. The first group in the list is called the Simulation Operation Parameters and includes the following information:

- Title for the run
- Vehicle configuration
- Initial velocity of the vehicle
- Steer input (steering angles or path to be followed)
- Braking inputs
- Simulation time
- Road description (flat, grades or user subroutine)
- Output (type and printing intervals)

The list next includes information to describe the truck or tractor, grouped in the order of sprung mass properties, front suspension and axle description, front tire and wheel properties, then rear suspension and axle, rear tires and wheels, and finally, the individual brake characteristics (if braking is used in the maneuver). If the vehicle configuration includes a semitrailer, the list of parameters continues with a description of its sprung mass properties, suspension and axle properties, tire and wheel properties, and brake characteristics. With doubles and triples combinations, the description of each trailer then follows in a similar

fashion. The full trailers of a doubles or triples combination may be of the fixed or converter dolly type.

The sprung mass properties are described by the following types of parameters, as illustrated for truck/tractors in Figure 1:

- Wheelbase (the characteristic length)
- Front and rear curb weights (weight)
- Center of gravity height
- Moments of inertia in roll, pitch and yaw
- Payload (weight, location and moments of inertia)
- Hitch point location (fifth wheel or pintle hook)
- Fifth wheel roll stiffness (with tractors only)

The payload is an option that facilitates easy simulation of a vehicle under different loading conditions. Hitch point information is required only when the unit being described is a tow vehicle for another trailer. The sprung mass information for a full trailer includes four additional parameters at the beginning of the list, which consists of a key for selecting fixed or converter dolly, and three dimensions that effectively describe the tongue length, location of the yaw articulation point, and location of the pitch articulation point.

The suspension and axle parameters describe the suspension and unsprung mass properties. These items are modeled as shown in Figure 2. Either a single or optional tandem axle may be specified at any axle location except the front axle of the truck/tractor unit. The descriptive parameters required are as follows:

- Suspension key (single or tandem)
- Tandem parameters (axle separation, static load distribution, brake torque load transfer effects)
- Spring rates
- Viscous damping and coulomb friction
- Axle mass and roll moment of inertia
- Roll center height

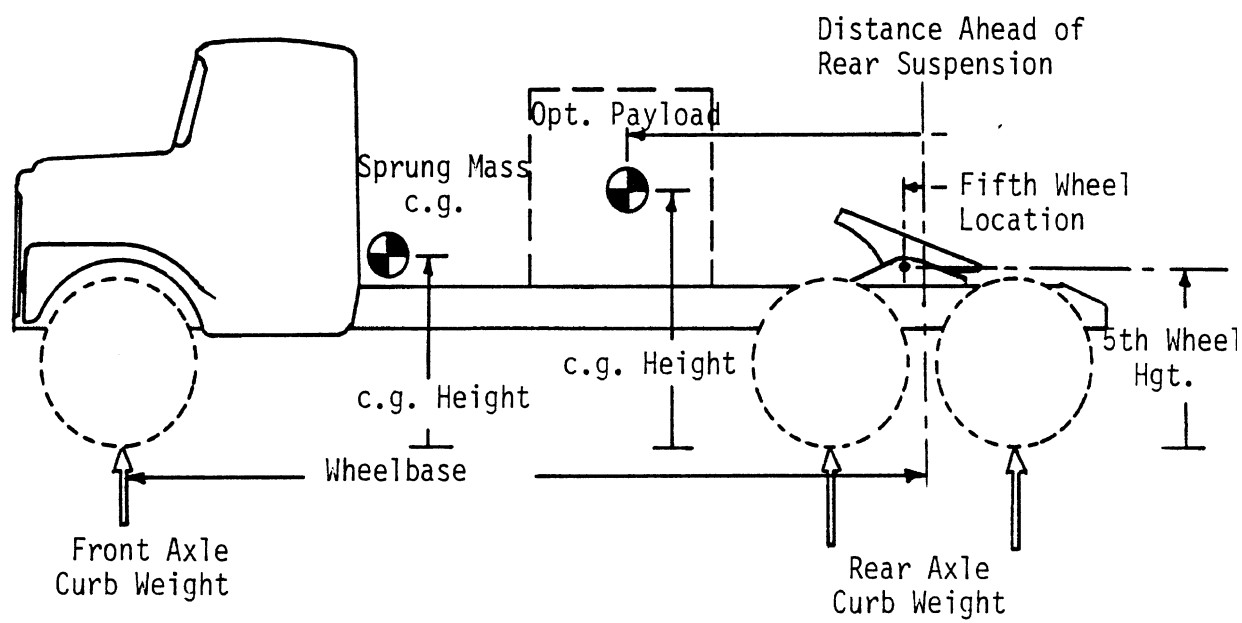


Figure 1. Modeling elements of the truck/tractor sprung mass.

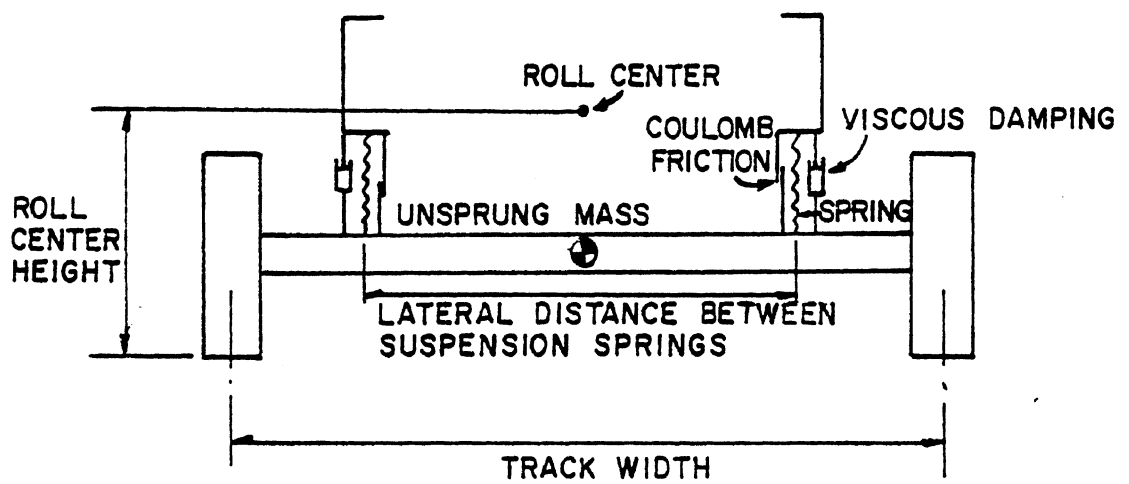


Figure 2. Model of suspension systems.

- Roll steer coefficient
- Auxiliary roll stiffness
- Lateral distance between springs
- Track width

Tandem axles are modeled as two single axles with static and dynamic load transfer interactions. The suspension spring rate may be given as a single (linear) characteristic; or by use of a negative integer entry, the program is keyed to accept a multi-point table to define nonlinear characteristics. In addition, the suspension properties may be given different values on the left and right side of the vehicle in a side-to-side option exercised by making a double entry on the specified line.

The tires and wheels are described by parameters that represent:

- Dual tire separation (except truck/tractor front axle)
- Tire stiffnesses (cornering, longitudinal, camber, aligning moment, and vertical spring rate)
- Tire loaded radius
- Polar moment of inertia

The stiffness values represent the elastic properties of the tire and its frictional coupling to the road surface. The cornering and longitudinal stiffnesses are especially significant to turning and braking performance, respectively. Hence, either may be entered as a multi-point table by use of the negative integer keying method described above. Additionally, the side-to-side option may be used with any of the above parameters.

Brakes are described by three parameters—a time lag and rise time representing the brake pressure transmission characteristics of the pneumatic lines to each brake, and the brake torque characteristics. The last parameter may be given as a multi-point table if so desired. Each brake of the vehicle may be described individually by each of the above parameters. Further, an antilock brake control may be specified for each wheel position. The antilock simulation is a general-purpose program which requires the user to define the operating characteristics of each antilock system being specified.

As input data is read, the data is normally "echoed" as the first pages of output. At the completion of the input read process, the program calculates necessary properties of the total vehicle combination and prints a page of output containing a summary of those vehicle properties. The program then "runs," solving the differential equations of motion for the vehicle until the vehicle reaches a full stop, a default stop (such as rollover), or until the designated maximum simulation time is reached. At various points during the run, simulation output is printed, which (at the option of the user) may include time-based values for the vehicle motion variables, tire forces at each axle, braking conditions on each axle, tire cornering conditions, and the suspension motions and forces.

The vehicle motion variables are given as instantaneous values of (translational and rotational) position, velocity, and acceleration. Auxiliary information on the radius of turn, body sideslip angle and articulation angles (of tractor-trailer vehicles) is also provided. The tire forces include vertical, lateral, and longitudinal components, the associated coefficients of friction being utilized, and the wheel operating conditions relating to steer and slip angles, brake torque, and wheel longitudinal slip. The suspension motions are defined by the vertical and roll positions and velocities. Suspension forces are those derived from spring deflections, damping effects and auxiliary roll stiffness.

### 2.3 Uses of the Program

The great versatility of the T3DRS:V1 program in representing commercial vehicle types and components in steering and braking maneuvers gives it great utility. It can be used to simulate the following vehicle configurations:

- Straight truck, empty and loaded
- Bobtail tractor
- Tractor-semitrailer (3 to 5 axles), empty and loaded
- Tractor-semitrailer-full trailer (5 to 9 axles), empty and loaded
- Tractor-semitrailer-full trailer-full trailer (7 to 13 axles), empty and loaded

For simulation of braking performance, the program incorporates representation of truck air brake systems, antilock wheel control systems and tire-road friction models. Typical examples of braking studies for which it can be or has been used are:

- 1) Stopping distance performance
- 2) Effects of brake timing
- 3) Dynamic behavior in braking
- 4) Comparisons of antilock wheel control logic
- 5) Influence of tire-road friction coupling
- 6) Split friction surfaces
- 7) Brake proportioning
- 8) Tandem-axle effects on braking limits

For simulation of cornering performance behavior, the program allows state-of-the-art representations of truck tire lateral force characteristics (with roll-off effects during combined braking), and vehicle suspension properties of significance to cornering behavior. Typical examples of studies involving cornering are as follows:

- 1) Understeer/oversteer properties of commercial vehicles
- 2) Determining cornering limits
- 3) Assessing the tandem-axle effects on cornering
- 4) Jackknife prediction
- 5) Effects of suspension properties on cornering and cornering limits
- 6) Accident simulation

In addition to the above, the program can be operated open-loop (defined steer angle inputs) or closed-loop (defined path input), on roads of specified grade or cross-slope, and on roads defined by the user.

## 2.4 Validation

The validity of T3DRS:V1, like any computer program, is dependent on the accuracy and execution of program statements, the capabilities of the simulation models, and the quality of the vehicle and maneuver descriptions defined by the input data. Throughout its development within the project, simulation results have been checked against analytical models, the predecessor simulation programs, vehicle test data acquired by this Institute and vehicle test data acquired by the Texas Transportation Institute (TTI) in the companion project "Validation of Truck Handling Simulation Results," [6].

Figure 3 shows a comparison of the T3DRS:V1 predictions of low-speed cornering behavior for trucks against analytical models and experimental data from another project [7,8]. The vehicle is a three-axle straight truck loaded to 44,500 lb (20,185 kg) gross vehicle weight. At the selected eight-degree steer angle, the program predicts a path curvature in agreement with the analytical model and experimental data. Similar agreement may be expected at other steer angles.

With increases in speed, steady-state cornering performance is commonly characterized by the change in road wheel steer angle with increasing lateral acceleration (understeer gradient). Figure 4 shows a comparison of T3DRS:V1 predictions with experimental data, and the earlier Phase II computer simulation [7,8]. The experimental data was acquired on the same test vehicle as in Figure 3 in steady-state cornering at different speeds and radii of turn. The T3DRS:V1 and Phase II simulations differ slightly, but inconsequently, in the understeer predictions due to slight differences in tire characteristics in the models. Both simulations exhibit limit behavior, indicated by inability to achieve a steady-state turn, at just over 0.3 g's lateral acceleration, as was observed on the test vehicle.

Transient behavior in a cornering maneuver should also be predicted correctly by a simulation. Figure 5 shows replication of a double lane change by the empty tractor-semitrailer combination tested by TTI. The lane-change path defined for the test maneuver was used as input to the simulation through the path-follower model. The front-wheel steer angle



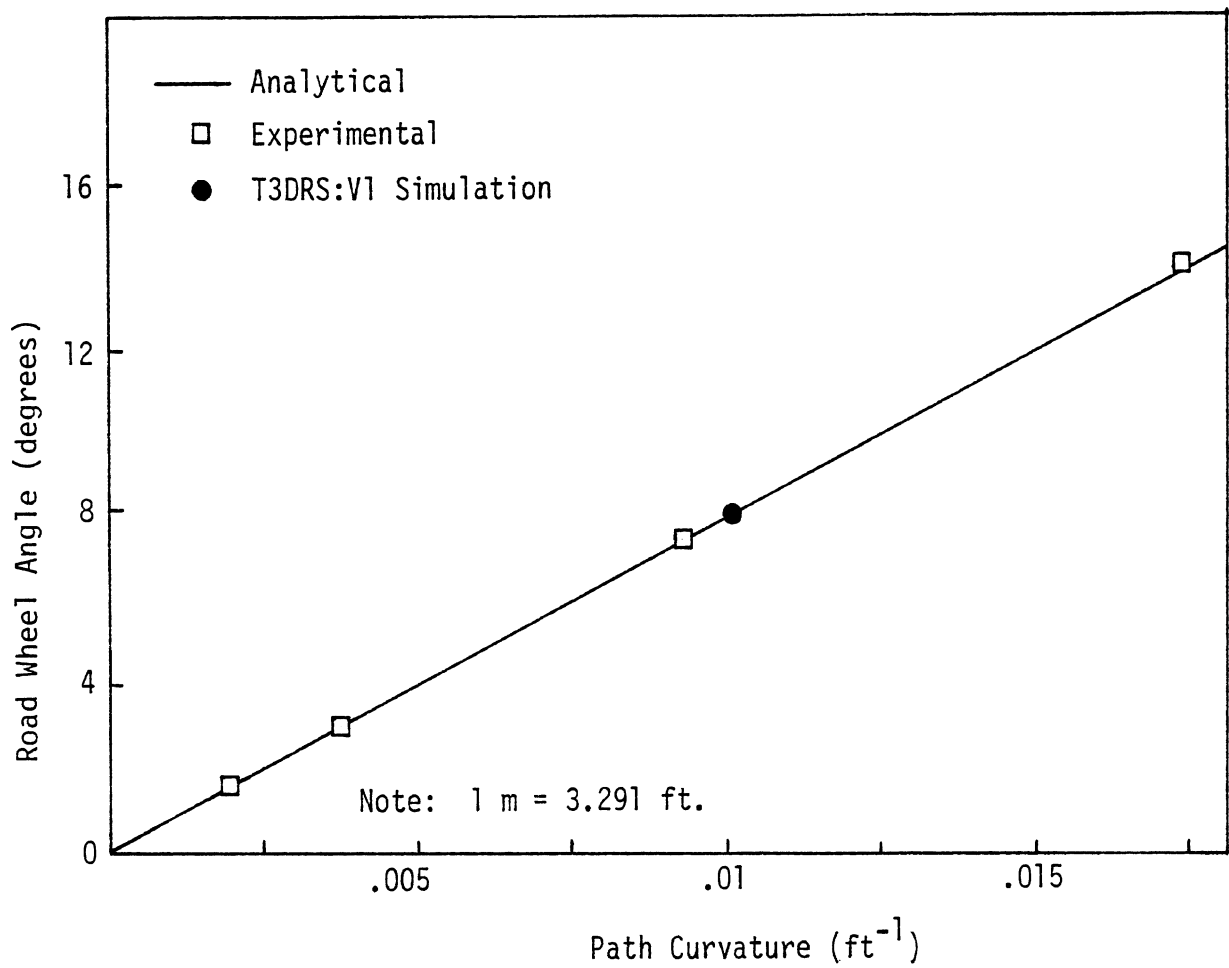


Figure 3. Comparison of analytical, experimental and simulation predictions for low-speed cornering of a loaded three-axle straight truck.

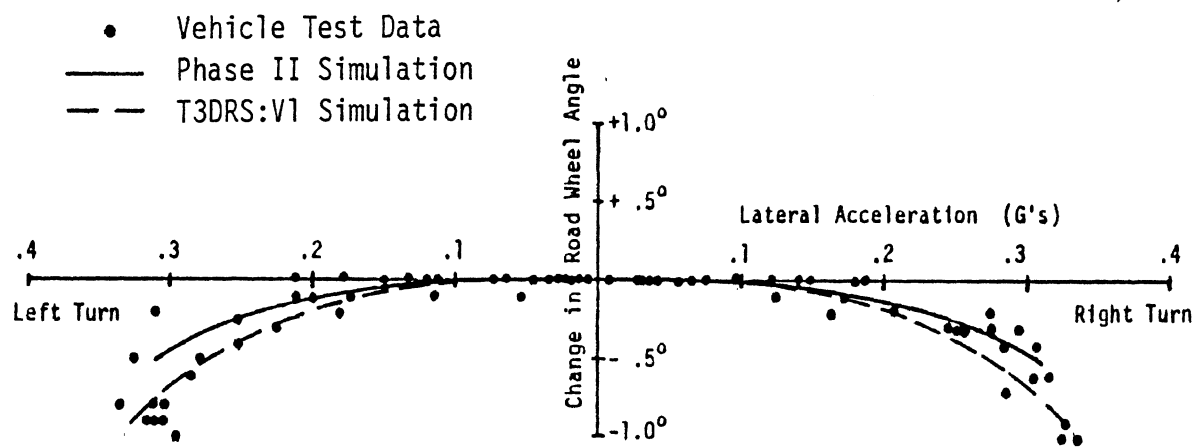


Figure 4. Comparison of experimental and simulated results for high-speed cornering of a loaded three-axe truck.

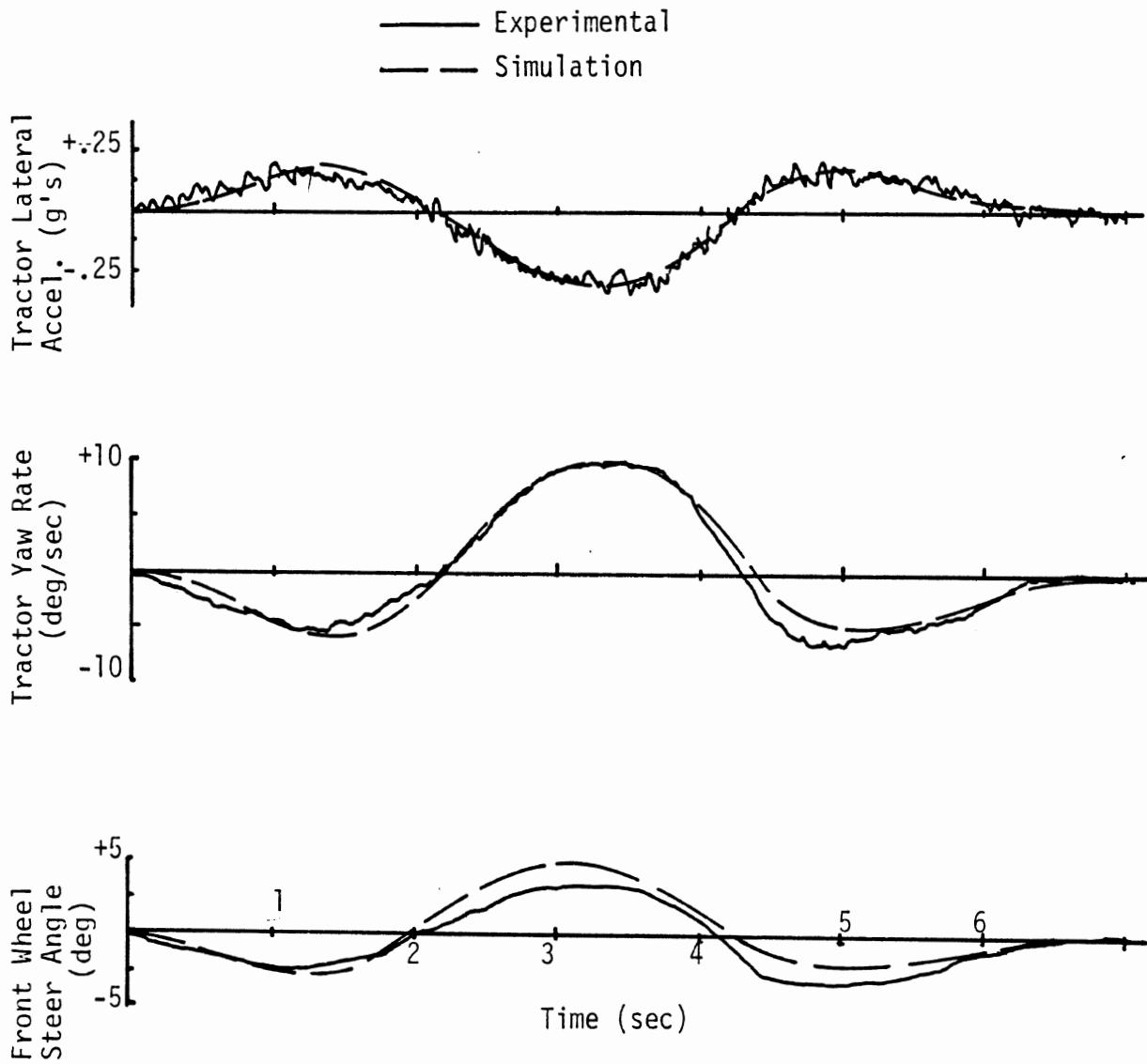


Figure 5. Comparison of simulation with experimental results in a double lane-change maneuver (TTI Test #199, empty, fifth wheel-midpoint, trailer bogey-rear).

assumed by the simulation closely matches that of the test vehicle, with similar agreement in the vehicle response variables of lateral acceleration and yaw rate.

Finally, a simulation may be used to predict braking performance, either straight-line braking or braking in a turn. Figure 6 gives an example of the T3DRS:V1 predictions of a tractor-semitrailer braking-in-a-turn maneuver performed at TTI. Close agreement with the actual behavior of the test vehicle is obtained.

Ultimately, the determinant of validity of a computer simulation program is the user-supplied input data and the interpretation applied to the results. Properly used, the program is capable of validly predicting most aspects of braking performance and directional response in maneuvers up to the limits of rollover. In the special case where a direct comparison between a vehicle and simulation (i.e., validation) is intended, the acquisition of accurate experimental measurements and vehicle parameters is costly and time-consuming. In most applications, however, the program is used as a tool for studying generalized performance and sensitivity of performance to vehicle parameters. In those cases, it is sufficient to simply use representative vehicle parameters, recognizing that the results obtained are typical but not precisely equivalent to any specific vehicle.

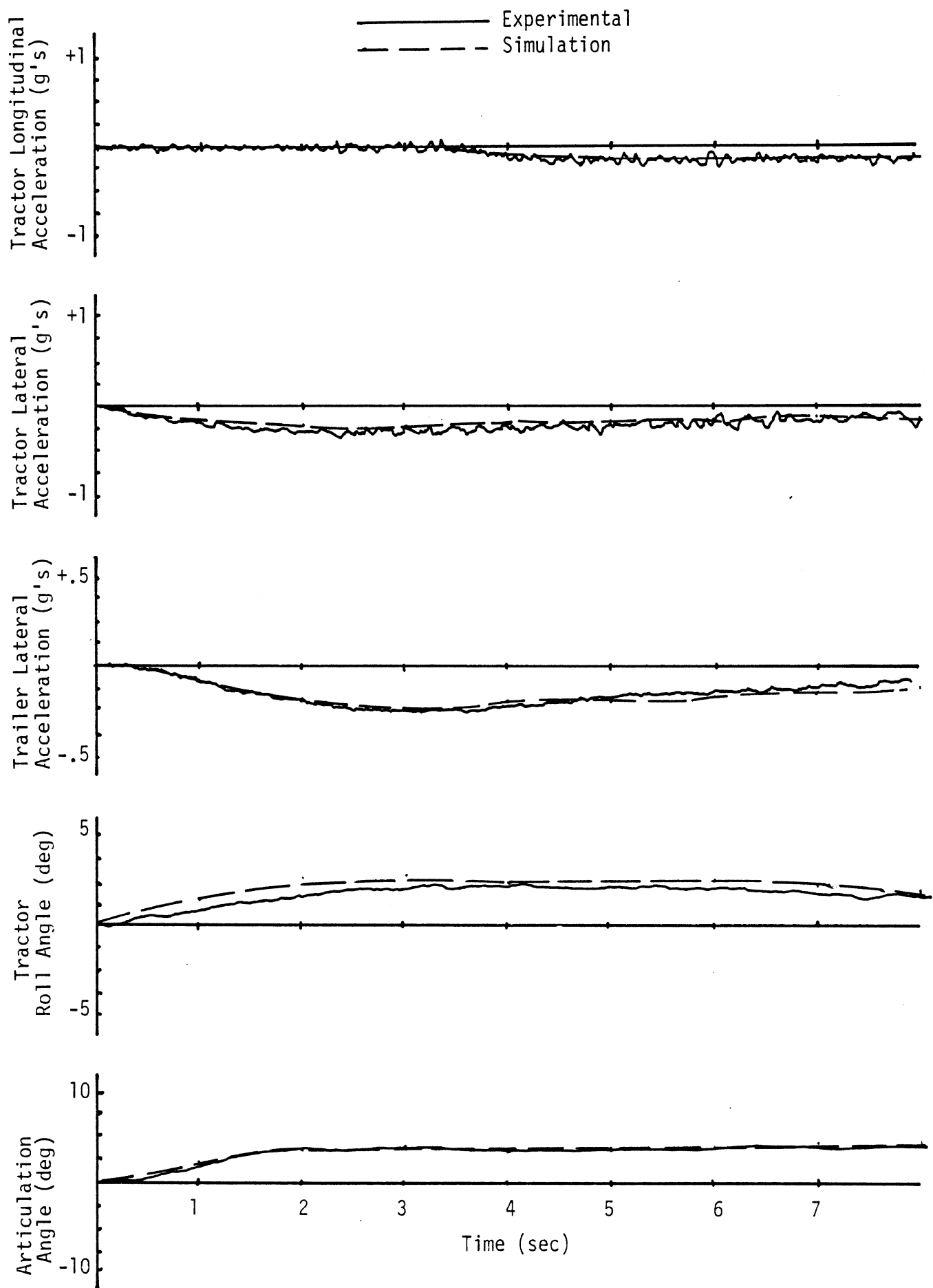


Figure 6. Comparison of simulation with experimental results in a braking-in-a-turn maneuver (TTI Test #287, loaded, fifth wheel-rear, trailer bogey-forward).

### 3.0 CONCLUSIONS

Inasmuch as this project has been primarily concerned with development of tools and methodology without actually making assessments of the effects of increased truck size and weight on dynamic behavior, the conclusions are limited to summary statements relating to the simulation program and its application to the problem.

The conclusions are as follows:

- 1) The T3DRS:V1 computer simulation program provided to the FHWA, in the opinion of HSRI, is considered to be the most versatile and easily used simulation currently available for investigating the dynamic behavior of heavy vehicles.

- 2) The subject program has been made operational on computer facilities designated by the FHWA, and use of the program by FHWA staff has been demonstrated.

- 3) The T3DRS:V1 program is capable of validly predicting braking and directional response behavior of trucks, tractor-semitrailers, doubles and triples.

- 4) The program is a suitable tool for studying the effects of truck size and weight through its capability to characterize performance changes in any selected maneuver with variations in size and weight.

#### 4.0 RECOMMENDATIONS

In order to fully utilize the products of this project, the HSRI recommends that:

1) The FHWA regularly use and maintain the computer simulation program at their facilities. The proper application of the program requires personnel with knowledge and experience in heavy vehicle simulation. Regular use will develop those skills. Failure to use a program usually results in its eventual relegation to a nonfunctional status.

2) The FHWA use the program in a systematic study of the effects of increased truck size and weight. The investigation should be directed toward identifying the dynamic performance changes associated with different size and weight limits as applied to vehicles of alternative design configurations. Specifically, the investigation can be used to identify vehicle design factors (such as tire or brake size) that should be upgraded as a condition for allowing increases in truck size or weight.

## 5.0 REFERENCES

1. Murphy, R. W., Bernard, J.E., and Winkler, C.B. "A Computer-Based Mathematical Method for Predicting the Braking Performance of Trucks and Tractor-Trailers." Phase I Report: Motor Truck Braking and Handling Performance Study, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, September 15, 1972.
2. Bernard, J.E., Winkler, C.B., and Fancher, P.S. "A Computer-Based Mathematical Method for Predicting the Directional Response of Trucks and Tractor-Trailers." Phase II Technical Report: Motor Truck Braking and Handling Performance Study, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-PF-73-1, June 1, 1973.
3. Winkler, C.B., et al. "Predicting the Braking Performance of Trucks and Tractor-Trailers." Phase III Technical Report, Truck and Tractor-Trailer Braking and Handling Project, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-76-26, June 1976.
4. Gillespie, T.D., MacAdam, C.C., and Hu, G.T. "Truck and Tractor-Trailer Dynamic Response Simulation - T3DRS:V1, User's Manual." Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-79-38-1, June 1979.
5. Hu, G.W., Bernard, J.E., MacAdam, C.C., and Gillespie, T.D. "Truck and Tractor-Trailer Dynamic Response Simulation - T3DRS:V1, Programmer's Manual." Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-79-38-2, September 1979.
6. Hayes, G. "Validation of Truck Handling Simulation Results." Final Report, Contract No. DOT-FH-11-9344, Texas Transportation Institute, College Station, Report No. RF-3660, August 1979.
7. Gillespie, T.D. and Winkler, C.B. "On the Directional Response Characteristics of Heavy Trucks." 5th VSD - 2nd IUTAM Symposium on Dynamics of Vehicles on Roads and Tracks, Vienna, Austria, September 19-23, 1977.
8. Gillespie, T.D. "Validation of the MVMA/HSRI Phase II Straight Truck Directional Response Simulation." Final Technical Report, MVMA Project #1.29, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-78-46, October 1978.